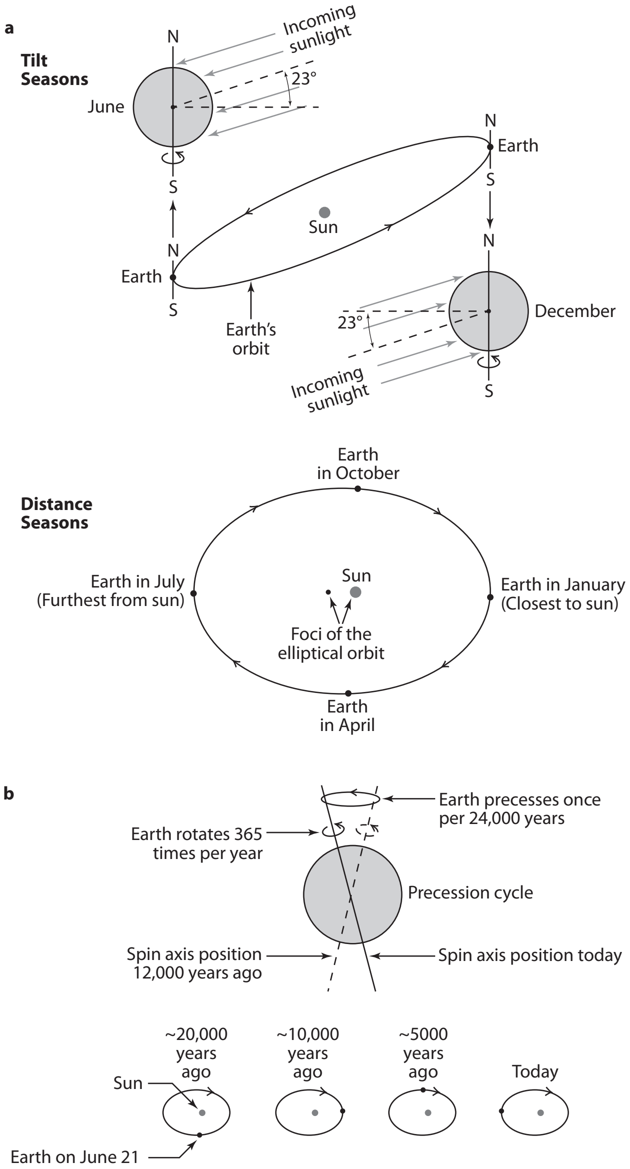
CHAPTER 1

The Setting

It was not until the mid-1980s that scientists became aware that our planet's climate system was capable of taking abrupt jumps from one state of operation to another. These jumps are the subject of this book. Before introducing them, however, we need to explore their context, namely, the stately progression of glaciations and interglaciations that are paced by cyclic changes in the configuration of the Earth's orbit (figure 1-1a).

Although, early on, physicists identified the precessing (that is, the slow gyration) and wobbling of our planet's spin axis as the likely drivers of the ice ages, geologists dragged their feet. In order to convince them that orbital changes were indeed the cause, during the 1920s and 1930s Milutin Milankovitch, a Serbian mathematician, made elaborate calculations elucidating the time sequence of seasonal changes in the amount of sunlight (i.e., solar insolation) reaching high northern latitudes. He reasoned that ice caps in North America and Europe likely grew during times of reduced summer insolation (that is, delivery of solar radiation) and retreated during times of enhanced summer insolation. In so doing, he hoped to provide geologists with a chronology to be compared with that for past glaciations. The problem was that, prior to World War II, geologic age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Sun
Earth on June 21

determination was in its infancy and hence incapable of providing the needed test. Thus, despite his painstaking calculations, Milankovitch failed to turn the heads of many of the day's paleoclimate specialists.

It was the postwar research of two professors at the University of Chicago that set the stage for the widespread acceptance of what had become known as the Milankovitch theory. Harold Urey, a chemist, demonstrated that the ratio of heavy oxygen (^{18}O) to light oxygen (^{16}O) in the calcium carbonate ($CaCO_3$) of seashells could be used to reconstruct past temperatures. Willard Libby, a physicist, harnessed a radioactive isotope of carbon, ^{14}C, to determine the ages of shell material formed during the last forty thousand years. Temperature and time, the two pieces of information required to determine whether or not Earth's climate has been paced by Milankovitch's orbital cycles, could now be determined.

What was lacking was a geologist with a vision regarding how to apply Urey's paleotemperature method to this problem. This vision was soon supplied by a young Italian, Cesare Emiliani, who, circa 1950, arrived in Urey's lab as a postdoc. He

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Figure 1-1

a. The two sources of seasonality: that resulting from the *tilt* of the Earth's spin axis with respect to its orbit and that resulting from changing Earth–Sun *distance*. Cyclic changes in obliquity lead to a 41,000-year period in the amplitude of tilt seasonality. Cyclic changes in the roundness (i.e. eccentricity of the Earth's orbit lead to a 100,000-year period in the amplitude of the distance seasonality.

b. The precession of the Earth's spin axis leads to an antiphasing between distance seasonality experienced by the Northern Hemisphere and that experienced by the Southern Hemisphere. Switches occur with a period averaging about 20,000 years. The period is a bit shorter than the 24,000-year precession time because of the 105,000-year rotation of the Earth's orbit.

proposed to use Urey's mass spectrometer to conduct precise oxygen isotope analyses on tiny shells of surface ocean-dwelling (i.e., planktic) foraminifera abundant in deep-sea sediments. In the parlance of scientists, the resulting article, published in the *Journal of Geology* in 1955, constituted not only a home run but one with the bases loaded.

Rather than the brief cold snaps (glaciations) separated by long periods of warmth (interglaciations) envisioned by the paleontologist David Ericson based on his record of the relative abundance of species of planktic species, the oxygen isotope results indicated an alternation of warm and cold episodes of roughly equal duration. Furthermore, the duration of these episodes based on the extrapolation of sediment accumulation rates determined using Libby's ^{14}C method yielded a reasonable match to those predicted by Milankovitch.

While Emiliani awakened the paleoclimate community to the likelihood that Milankovitch had it right, one aspect of his interpretation of his results came under fire. He concluded that the glacial to interglacial cycles were accompanied by large (~7°C) swings in tropical ocean temperature. Emiliani was aware that the isotope composition of the oxygen in his shells was influenced not only by the temperature of the water in which the foraminifera grew but also that the waxing and waning of the ice sheets changed the isotopic composition of the ocean water in which they grew. The snow falling on the Greenland and Antarctic ice caps has an ^{18}O to ^{16}O ratio several percent lower than that of seawater. Hence, the growth of ice sheets must have led to an enrichment of ^{18}O in the sea. So, both cooling and ice growth contributed to the higher ^{18}O to ^{16}O ratio in foraminifera shells formed during times of glaciation. The problem was to estimate their relative contributions to the ^{18}O enrichment. Emiliani concluded that temperature dominated over ice volume.

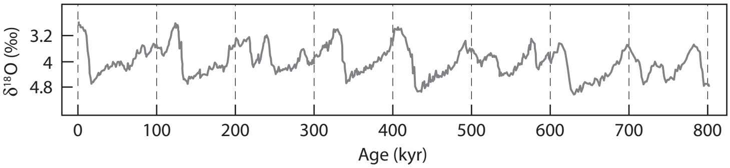

Figure 1-2. Benthic foraminifera ^{18}O to ^{16}O record for the past 800,000 years as obtained by Maureen Raymo of Boston University.

This conclusion was challenged by Nicolas Shackleton, a graduate student at Cambridge University whose great uncle, the explorer Ernest Shackleton, had been marooned in Antarctica's Weddell Sea when his wooden ship was crushed in the ice. Nicolas sought to check Emiliani's interpretation by doing oxygen isotope analyses on the bottom-dwelling shells of foraminifera (i.e., benthics). Shackleton's reasoning was as follows. As the temperature of deep seawater is already close to the freezing point, the contribution of temperature to the glacial enrichment of ^{18}O would have to be quite small. The problem he faced was the scarcity of benthics. It was not possible to get enough to provide the amount of sample required by the mass spectrometers of the time. So, Sir Nick,[1] as we now refer to him, set about to improve his mass spectrometer so that it could make accurate measurements on much smaller samples. It took several years before he succeeded. But the effort paid off. The oxygen isotope record for benthics had the same glacial to interglacial amplitude as Emiliani had found for planktics (see figure 1-2). This led Shackleton to conclude that ice volume rather than temperature dominated. After many years and many arguments, the

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[1] Nicolas Shackleton stayed on at Cambridge and established himself as the dean of Cenozoic marine stratigraphy. His incredible list of accomplishments earned him not only important awards and membership in the Royal Society, but also a knighthood. Hence, "Sir Nick."

situation has finally settled down to a 60–40 split. About 1.05 per mil of the 1.75 per mil range in ^{18}O to ^{16}O ratio in the foraminifera records is the result of ice volume and about 0.70 per mil is the result of cooling. Hence, glacial-age tropical surface water cooled by only about 2.5°C instead of the whopping 7°C estimated by Emiliani.

Another contentious point was the age of the termination of the penultimate glaciation. Because the early ^{14}C measurements provided a reliable chronology back only about 30,000 years, some other chronometer was needed to reach further back in time. The obvious choice was ^{230}Th, an isotope with a 75,000-year half-life produced by the decay of uranium. Early on, this isotope was used to directly date deep-sea sediments. The approach took advantage of the fact that the ^{230}Th produced by the radioactive decay of uranium[2] dissolved in seawater was quickly absorbed onto particles and carried to the sea floor, providing newly deposited sediments with a large excess of this isotope. The radiodecay of this excess ^{230}Th provided the basis for sediment dating. This application was plagued, however, by the requirement that some means had to be adopted to take into account variations with time of the concentration of ^{230}Th in newly formed sediment. Two approaches were used. One, adopted by scientists at Columbia University, yielded an age of about 125,000 years for the end of the penultimate glaciation. Another, adopted by scientists at the University of Miami, confirmed Emiliani's original estimate of about 100,000 years.

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[2] The ^{230}Th is produced by the decay of ^{234}U, which is a 254-kyr half-life daughter product of ^{238}U. It came as a surprise when a Russian geochemist discovered that ^{234}U and ^{238}U were separated when rocks are weathered. The reason is that, during their formation by alpha particle decay, the ^{234}U atoms are knocked loose and hence are preferentially released to solution. Seawater has a 15 percent excess of ^{234}U over that expected were it at steady state with its parent ^{238}U.

The argument over which of these approaches gave the best answer was an important one, for the 125,000-year age yielded a much better match to the Milankovitch summer insolation record. Once again, when the dust finally settled, Emiliani ended up on the wrong side of the argument. Although these two issues took a bit of shine off his efforts, the publication of Emiliani's 1955 article certainly marked the turning point in thinking regarding the pacing of the ice ages. He made it clear that Milankovitch had it right!

Even though Emiliani's article turned the tide, dissenters intensified their volley of criticism, as is often the case when major paradigm shifts occur. Further evidence in support of Milankovitch was needed! By serendipity it came when Robley Matthews, a geologist at Brown University, learned that the isotope ^{230}Th could be used to date corals. This new method was, in a sense, the inverse of that used to date marine sediments. Because ^{230}Th is efficiently stripped from seawater,[3] next to none is available to be built into corals. On the other hand, corals incorporate uranium as if it were calcium (i.e., the U to Ca ratio in corals is close to that in seawater). Then as coral ages, the ^{230}Th produced by the decay of uranium within the coral accumulates like the sand in the bottom of an hourglass. This buildup of ^{230}Th serves as a clock. Matthews asked David Thurber, a graduate student at Columbia University, to analyze two corals he had collected from raised terraces on the island of Barbados. His goal was to determine the rate at which the pore space in corals was filled in by diagenesis (something petroleum geologists were interested in, for ancient coral reefs constitute one of their favorite reservoirs).[4] When Thurber finished the analyses, there was great excitement

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[3] The element thorium has a very strong tendency to attach itself to the water column particulates. Hence geochemists refer to it as a particle-reactive element.

[4] *Diagenesis* refers to chemical alteration of sediments as a result of mineral-pore fluid interactions.

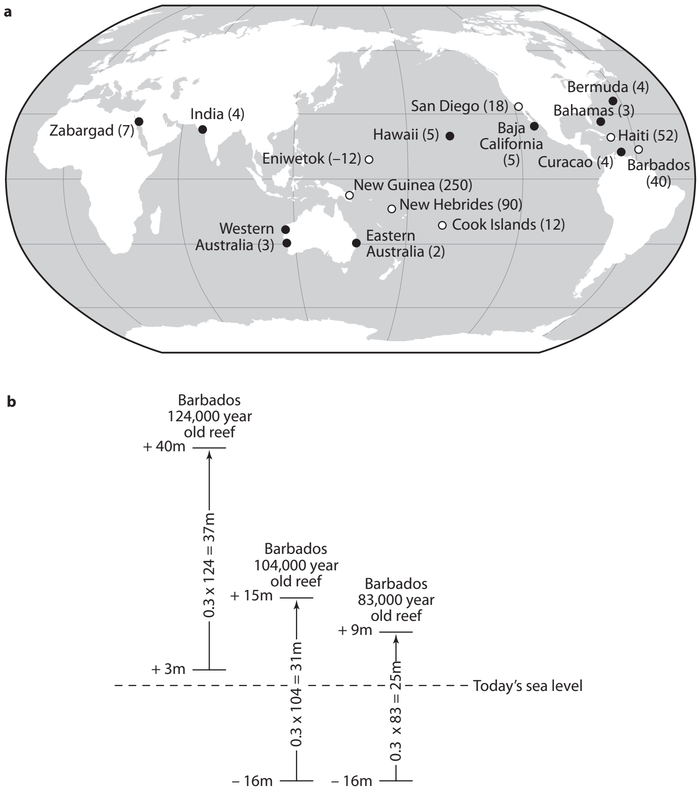

Figure 1-3

a. Locales where the 124,000-year old interglacial high sea stand has been radiometrically dated by the ^{230}Th-^{234}U method. The numbers represent their present-day elevations in meters. The solid circles represent tectonically stable coastlines, and the open circles from shorelines undergoing tectonic uplift.

b. Elevations of the three raised coral reefs on the island of Barbados. Based on the 3-meter height of the last interglacial sea stand (as determined on stable coastlines), the average uplift rate of Barbados has been about 0.3 meters per kyr. Based on this rate, 105,000 years ago and 83,000 years ago the sea stood about 16 meters below its present level. Keep in mind that at the peak of the last glacial period it stood about 120 meters lower than it does today.

in our lab because the age of one coral came out close to 124,000 years[5] and the other close to 83,000 years. Both were times when Milankovitch's calculations yielded maxima in Northern Hemisphere summer insolation and, accordingly, glaciers should have melted back, raising sea level (see figure 1-3). When asked about the setting of his coral terraces, Matthews explained that Barbados was being underthrust by the Atlantic's oceanic crust. As a consequence, it was being uplifted, pushing above sea level coral reefs formed during times when the sea stood lower than at present. Matthews then surprised Thurber by mentioning that there was a third coral terrace situated between the other two (i.e., below the elevation of the 125-kyr coral terrace and above that of the 83-kyr coral terrace). Thurber was eager to determine its age. The result turned out to be about 105,000 years. At first this was puzzling because the Milankovitch reconstruction had no peak in summer insolation at that time. This puzzle was resolved when it was realized that the Milankovitch reconstruction placed too much emphasis on the contribution of the 40,000-year obliquity cycle (i.e., the rocking of the Earth's orbit that alternately strengthened and weakened the tilt seasonality) and too small a contribution of the ~20,000-year precession cycle. Calculations based on a different choice of latitude than that chosen by Milankovitch led to a greater contribution of precession and produced a summer insolation peak at 105,000 years ago. Hence, Thurber's finding that the sea level reached three successive maxima in concert with three summer insolation peaks spaced at 20,000-year intervals provided confirmation that Milankovitch cycles paced fluctuations in the size of the Earth's ice sheets.

An even stronger verification based on an analysis of the spectral makeup of benthic foraminifera oxygen isotope records

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[5] This age turned out to mark the onset of the last interglacial interval and was key to the resolution of the argument over the timing of this event.

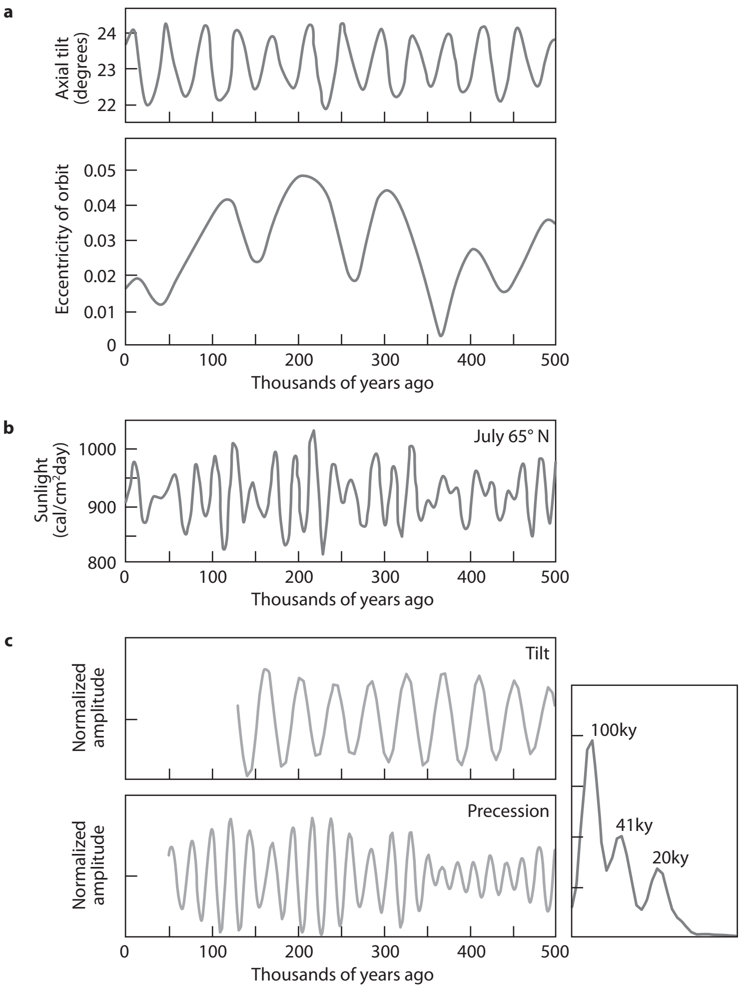

Figure 1-4

a. The Earth's axial tilt and orbital eccentricity over the past 500,000 years as determined by celestial mechanics.

b. July solar irradiance at 65°N over the past 500,000 years.

c. Amplitude of the 41,000- and 20,000-year spectral components of the benthic foraminifera $^{18}O/^{16}O$ record (dashed curve) compared with that of the tilt (i.e., obliquity) and distance (i.e., eccentricity–precession) came some years later. This effort, spearheaded by John Imbrie, a paleontologist at Brown University, showed that three periodicities dominated the benthic record, one close to 20,000 years ago, one close to 40,000 years, and one close to 100,000 years (figure 1-4). The first two of these were, as expected, reflecting the 20,000-year precession and the 40,000-year tilt cycles. The finding of the third periodicity (i.e., 100,000-year), however, created a puzzle that even today has not been satisfactorily resolved. Over the better part of the past million years, the oxygen isotope record for benthic foraminifera has undergone a cycle with an asymmetrical triangular shape. Long intervals of cooling accompanied by growing ice sheets terminated during relatively short time intervals, returning climate to its full interglacial condition. In other words, as the glacial world warms, the ice sheets melted away.

When examined in detail, however, the spacing between these terminations was never exactly 100,000 years. Rather, it was either close to 80,000 or close to 120,000 years. This gives the impression that during each glacial episode the Earth system drifted toward some sort of instability that, when reached, triggered a jump back to the warm state. Furthermore, these jumps occur preferentially during episodes of strong Northern Hemisphere summer insolation. But the exact nature of the instability that produces the termination remains a mystery.

Several kilometer-long cores drilled through the Antarctic and Greenland ice caps turn out to be the Rosetta stones of the

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contributions to seasonality (solid curve). Due to "end" effects in the spectral analysis, the most recent several cycles had to be excluded. Also shown (to the right) is a so-called power-spectrum of a deep-sea ^{18}O record. This figure is reproduced from a paper authored by John Imbrie. This long-accepted evidence in support of insolation forcing has recently been challenged by Harvard's Peter Huybers. He shows that it is an artifact of the analysis procedure.

Ice Ages. The variety and detail of the information they contain is staggering. While the 800,000-year-duration record in Antarctic ice is dominated by the smooth cyclic variations orchestrated by the Milankovitch insolation cycles, that in Greenland is so riddled with the impacts of millennial-duration events that the Milankovitch imprint is largely masked. Furthermore, the record in Greenland covers only the past 130,000 years.

Building on the success of an American ice core from Byrd Station, Antarctica, Russian scientists decided to attempt to get a much longer record by drilling on the frigid polar plateau. Lacking transport aircraft, their scientists were forced to remain at the site year-round. During one of the frigid winters, their generator broke down and they survived by huddling in an ice cave heated only by candles. Despite this and other incredible hardships, after five long years they prevailed and penetrated 90 percent of the way through the ice cap. But, alas, they had no way to get the hundreds of tons of ice back to their laboratories. So it remained unanalyzed, stacked like logs at the frigid drill site.

Claude Lorius, a French scientist, realizing the immense value of this ice archive, negotiated an amazing deal. The ice would be flown out of Antarctica on American C147 cargo planes equipped with skis designed for snow landings and takeoffs. Part of the ice would go to a stable-isotope laboratory in France. Thus the first record of south polar temperatures covering several 100,000-year cycles was obtained. It revealed a surprise. As the precession cycle is antiphased between the hemispheres, if Milankovitch cycles were pacing climate, it would be expected that the 20,000-year periodicity in southern temperatures would be antiphased with that in the benthic ^{18}O record, which reflects the size of the northern ice sheets. Contrary to expectation, both records follow the tune of summer insolation at high northern latitudes. The reason for this remains a mystery.

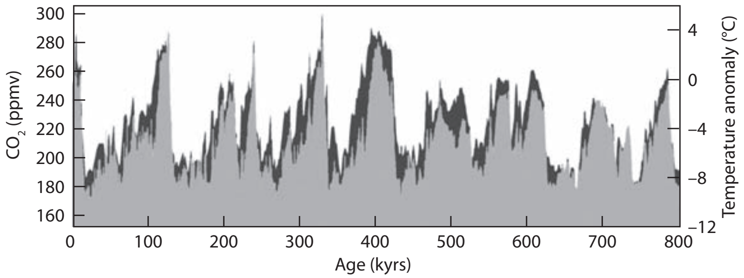

Figure 1-5. Record over the past 800,000 years from the Dome C Antarctica ice core of stable isotope–based temperature departures from today's (gray) and CO_2 contents of air trapped in bubbles (black) as obtained by French scientists.

In addition to a record of south polar temperatures, Antarctic ice contains a beautiful record of the changing trace gas composition of the Earth's atmosphere. Air bubbles trapped during the conversion of fluffy snow to solid ice constitute a pristine archive. Much information of great importance to our understanding of climate change is contained in this trapped air. Clearly, greatest interest is focused on the record of the atmosphere's CO_2 content. Measurements carried out in laboratories in both Bern, Switzerland, and Grenoble, France, showed that during times of peak glaciation, the CO_2 content of air was about 30 percent lower than during times of peak interglaciation. Furthermore, the shape of the CO_2 record is similar to that for oxygen isotopes in benthic foraminifera, faithfully following the stately Milankovitch pacing (but only weakly participating in the millennial disruptions that will concern us in the chapters that follow). And, as CO_2 is an important greenhouse gas, these ups and downs certainly contributed to the temperature changes that accompanied glacial cycles. Subsequent drilling by the European (EPICA) group at the polar plateau Dome C site yielded ice dating back to 800,000 years ago (see figure 1-5). Two aspects of this record are of particular interest. The first is the amazing similarity in the shape of the CO_2 and temperature records. The CO_2 content of the atmosphere is closely tied to the air temperature over the ice cap. The second is that both follow the Northern Hemisphere's summer insolation.

As there is currently no radiometric means of directly dating ice, initially the chronologies proposed for the Antarctic record were based on one or the other of two strategies. One took advantage of the similarity between the ice core and benthic foraminifera oxygen isotope records, and adopted the marine chronology. The other was based on the present-day rate of snow accumulation at the core site coupled with assumptions regarding the dependence of this rate on temperatures as reconstructed from the stable-isotope record. Of course, account also had to be taken of the thinning that occurred as the ice flowed toward the edges of the cap. As these two approaches agreed reasonably well, initially scientists were satisfied. As time went on, however, it became evident that a more precise chronology was needed if small leads on lags with respect to other records were to be reliably established.

Michael Bender, a scientist at Princeton University, came up with a clever means of tying the ice chronology directly to that for local Milankovitch's summer insolation cycles. As the latter chronology is based on rigorous celestial mechanics (i.e., on Newton's laws of gravity), it is highly precise. Bender's discovery came about somewhat by serendipity. He set out to make very accurate measurements of the ratio of O_2 to N_2 in the trapped air. His idea was that he might be able to detect the very small decreases in atmospheric O_2 during glacial time expected as the result of the oxidation of organic matter as the cold conditions killed the boreal forests. But he was disappointed (and puzzled) to find that the variations were far larger than could be attributed to vegetation oxidation. Intrigued as to what else could be the cause, he persisted and constructed an O_2/N_2 record that extended back several hundred thousand years. He was amazed to find that the fluctuations correlated beautifully with the amount of Antarctic summer insolation. He reasoned that this correlation was related to the observation that the greater the solar heating, the larger the individual ice crystals formed as the snow recrystallized. Perhaps the size of the ice crystals influenced the geometry of the "walls" surrounding the air bubbles as they were closed off in the final stage of lithification (i.e., the conversion of snow to solid ice). As closure occurs at a depth of many tens of meters, the air in the newly formed bubbles is under pressure. Hence, some is forced out through the remaining tiny orifices. As O_2 and N_2 molecules differ in size, Bender hypothesized that they are differentially squeezed out of the bubbles. As the extent of this separation would likely depend on the size of the ice crystals, it would also depend on summer insolation, Bender was able to make the case that his O_2 to N_2 ratio results created a firm tie to the local insolation changes created by the wobble of the Earth's orbit and the precession of its spin axis! The fact that the chronology he created in this way agreed quite well with the previous ones put to rest any lingering doubts regarding the validity of the Antarctic timescale.

One more record must be mentioned before we turn to the millennial-duration blemishes that mar the smooth swings paced by the Earth's orbital cycles. It is a record of the strength of the Asian monsoons contained in the stalagmites from caves in China. As with the record in marine foraminifera shells, it is based on ^{18}O to ^{16}O measurements on $CaCO_3$ (in this case stalagmite calcite). The chronology for the record is obtained in the same way as that for corals. Uranium picked up as rainwater percolates through the soil that overlies the cave is built into the calcite. But, as thorium remains behind safely locked in the soil, little accompanies the uranium. The ages are calculated by the amount of ^{230}Th that is subsequently built into the stalagmite by

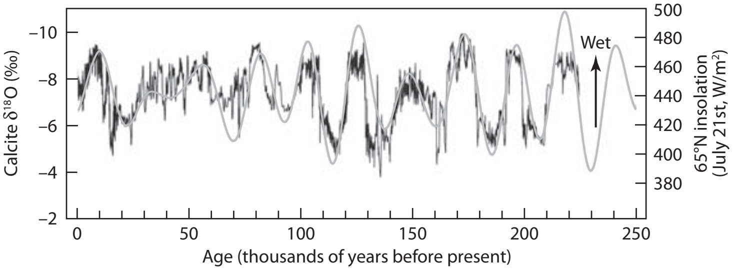

Figure 1-6. Strength of the East Asian monsoon as recorded by the ^{18}O to ^{16}O ratios in calcite from China's Hulu, Dongge, and Sanbao Caves. As shown by the smooth curve, the strength of the monsoon closely follows summer insolation at Northern Hemisphere high latitudes. The chronology was determined by precise ^{230}Th–^{234}U dating at the University of Minnesota by Larry Edwards and Hai Cheng in cooperation with Chinese colleagues Wang Yongjin, Yuan Daoxian, and An Zhisheng, who kindly permitted them to be reproduced here.

the decay of uranium. As a graduate student at Caltech, Larry Edwards developed a mass spectrometric method to measure ^{230}Th (and also its parent, uranium). He demonstrated that in this way he could improve the measurement precision by an order of magnitude over that obtained by the decay-counting method used by Thurber to date Barbados corals. As a professor at the University of Minnesota, Edwards reduced the analytical uncertainty of his mass spectrometry method by yet another order of magnitude and demonstrated that it could produce fantastically precise ages. For example, he now is able to achieve an accuracy of ±60 years on samples with an age of 100,000 years. (By comparison, Thurber's errors by the decay-counting method were several thousand years!) The only other chronology with this level of accuracy is that for the seasonality of solar insolation, which is based on celestial mechanics. Working with Chinese postdoctoral fellows and graduate students, Edwards has been able to piece together results that together provide a continuous oxygen isotope record extending back more than 200,000 years (see figure 1-6). This record has been replicated in three caves. Although the same small temperature and ice volume–related ^{18}O changes recorded in foraminifera must be present, the ^{18}O to ^{16}O ratio variations in Chinese stalagmites are much larger. They are dominated by variations in the contribution of monsoon rainfall to the total annual rainfall.

The main feature of the stalagmite record is its remarkable resemblance to that of 65°N summer insolation. As the monsoons are driven by the summer heating of the Asian continent, this is not unexpected. What is surprising is that the 100,000-year cycle that dominates both the benthic foraminifera record and the Antarctic ice record is only weakly expressed. On the other hand, the millennial events, which are this book's main focus, show up beautifully as marked negative deviations from the summer insolation trend. We will, of course, have more to say about these deviations in the chapters that follow.

Before we leave this introduction, a few words are needed about the questions it raises. Clues to their answers will be found in information contained in the record of millennial fluctuations.

1) Why can't the world's most advanced atmosphere–ocean models reproduce the impacts of Milankovitch insolation cycles as seen in the paleoclimate record? As we shall learn from our consideration of the impacts of the abrupt millennial events, the system has powerful feedbacks related to the way the ocean circulates and to the presence of sea ice.

2) Why does the cycle of the Northern Hemisphere ice sheets have an asymmetric saw-tooth shape? Key to the answer of this question is the understanding of the abrupt terminations of each 100,000-year cycle. To date we lack this understanding.

3) Why does the temperature in Antarctica appear to follow the pacing of the Northern Hemisphere's orbital cycles? The

answer to this question likely lies in what we shall refer to as the ocean's bipolar seesaw.

4) What mechanism allowed the ocean to suck in and breathe out CO_2, thereby generating the glacial-interglacial cycle in the atmosphere's content? Despite many attempts over the past twenty-five years, no entirely satisfactory explanation has been forthcoming. But as we shall see, it very likely has to do with sea ice cover around Antarctica.

5) Why doesn't the strength of the Asian monsoons show a more pronounced influence of the asymmetrical saw-toothed cycle so evident in the other records? As we shall see, although the strength of the Asian monsoons is strongly affected by the presence of sea ice, it does not appear to follow the change in size of the ice caps on land. This suggests that heat released from the sea is critical!